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Design and Safety in a New Chemical Engineering Research Laboratory at the University of Kansas

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Abstract

The University of Kansas School of Engineering and College of Liberal Arts and Sciences have experienced significant growth with the addition of nearly 600,000 square feet of new teaching and research space. The investment of more than $250 million in the past six years in new buildings with state-of-the-art laboratories has attracted many new faculty and students. This paper describes the safety features and equipment incorporated into the design of a new chemical engineering research laboratory. The main topics include: building layout and laboratory design, laboratory safety equipment and features, chemical safety and safety management and training. Specific examples involving design of custom ventilated enclosures, safety interlock systems, flammable gas storage and gas detection systems will be highlighted. A simple yet effective hazard analysis checklist will also be presented for identifying hazards and level of hazard review required.

Keywords: Laboratory safety; Chemical safety; Safety management; Safety training; Safety equipment; Safety design

Introduction

How to teach and implement safe practices in academic laboratories is critically important, particularly with the unique challenges faced in comparison to industrial research. For example, academic research can have frequent personal turnover (e.g., graduate students 2 to 4 years, post-doctoral researchers 1 to 2 years, undergraduate researchers, 3 to 12 months) which requires special attention to management of change issues. The inexperience of undergraduate and incoming graduate students to chemical and process safety must also be constantly recognized and repeatedly addressed. Academic research laboratories also contain a variety of hazards (chemicals and equipment) and students may often be performing relatively complex reactions near each other while sharing the same laboratory space. These challenges make it necessary to establish a strong safety "culture" which requires leadership, teaching, communication, collaboration and active participation by all members of the lab group, department or center [1]. Successful implementation of laboratory safety should consist of inherent, passive, active, and procedural approaches. Inherent safety techniques consist of minimizing hazards by using less hazardous chemicals and experimental/process conditions [2]. Passive safety techniques use the natural environment to reduce hazards by using smart processes and equipment without implementation of additional equipment [3]. Active techniques consist of using controls, interlocks, and emergency shutdown systems to monitor and act correctively if a process is outside of the designed limitations [4]. Procedural strategies use a personnel and system management approach to minimize the effects or chance of an incident [5]. Some examples of procedural strategies include process safety management (PSM), establishing a standard operating procedure (SOP), conducting routine laboratory inspections, and establishing an emergency response plan.

For chemists and chemical engineers, it is understood that the key to a strong safety culture begins in the classroom. Establishing a strong safety based culture at the undergraduate level can instill a sense of safety awareness in an individual that can be used throughout their career [6]. The American Chemical Society (ACS) has stressed the need for chemical safety education for many years [7]. For example, the ACS Committee on Professional Training (CPT) has suggested that safety should be implemented into the chemical collegiate curriculum [8,9]. Furthermore, a recent CPT publication on the Guidelines for Laboratory Safety in Academic Institutions outlines the learning objectives for undergraduates and provides guidance on a number of safety issues for researchers at the graduate, postgraduate, and continuing education levels [7]. The guidelines teach the acronym RAMP or to Recognize the hazards, Assess the risk, Minimize the risk, and Prepare for emergencies [10]. Furthermore, the guidelines suggest that chemical safety should be an integral part of the curriculum and all laboratory experiences to help prepare students to be safe and successful professionals. The ACS Joint Board-Council Committee also publishes a book explaining the best practices for college level students which can be an excellent introductory resource for students entering the lab [11].

In addition to chemical safety, it is essential for chemical engineers to have a firm understanding of chemical process safety. Chemical process safety is broadly focused on reducing the risks and environmental impact associated with a chemical process. As previously mentioned, the key to a strong safety culture begins in the classroom and the American Institute of Chemical Engineers (AIChE) has established the Center for Chemical Process Safety (CCPS), which is an industry alliance formed to promote process safety, following the toxic gas release in Bhopal, India in 1984 [12].

The center created the Safety and Chemical Engineering Education (SACHE) program, first known as the Undergraduate Education Committee, which strives to develop concepts to improve process safety, develop and distribute safety guidelines to plants, promote process safety as an industrial value, and develop materials to aid professors in teaching process safety in the classroom [13]. The AIChE Center for Chemical Processes has established a Risk Based Process Safety (RBPS) management framework consisting of four pillars which include: commitment to process safety, understanding the risks and hazards, managing the risk, and learning from experience [14]. The four pillars contain twenty subsections intended to establish a formal means of reducing the risks involved with handling, using, or manufacturing hazardous substances and/or energy. Although some aspects of the teachings are focused on industrial practice, the same concepts can be taught and applied in academic classrooms and research laboratories. The University of Kansas Department of Chemical and Petroleum Engineering requires that all chemical engineers take a Process Safety and Sustainability course typically taught in their Senior year. The course is designed to acquaint students with risk-based process safety and sustainability. Topics include elements of process safety management with historical and contemporary case studies of major accidents in the chemical and petroleum industry, overview of current government regulation (e.g., OSHA, EPA) and ethics. Students also receive an introduction to sustainable green chemistry and engineering principles and Life Cycle Analysis (LCA) to compare processes and products.

Much of the literature in the safety education field covers theory, statistics, and teaching with few examples of implemented safety systems and management in the academic setting [15]. The goal of this paper is to provide an example of the laboratory safety features and equipment integrated into the design of a new chemical engineering research laboratory at The University of Kansas and to provide information for individuals wanting to implement similar practices.

Background, Building Layout, and Laboratory Design

In 2011, the Kansas Legislature passed the University Engineering Initiative Act (UEIA) which appropriated $105 million dollars to Kansas Engineering Schools [1]. The money was provided to support Wichita State University, Kansas State University and The University of Kansas engineering programs with a mission to increase the number of engineering graduates and was initiated to meet the increasing demand for engineers in the Kansas region. The University Of Kansas School Of Engineering implemented a two-phase expansion project that added 186,000 square feet of teaching and research space as shown in Figure 1.

The Measurement, Materials and Sustainable Environment Center (M2SEC) was finished in August of 2012 and is a 47,000 square foot research facility that houses a variety of interdisciplinary research projects creating innovation in sustainable energy, alternative fuels, climate change, and the healthcare fields. Phase 2 added the Learned Engineering Expansion Project (LEEP2) building which provided 139,000 square feet of additional teaching and laboratory space. The laboratory space is designed to be flexible and can meet the needs of incoming faculty from a variety of engineering disciplines. In January 2018 the Earth, Energy, and Environment Center (EEEC) opened with 130,000 square feet of new laboratory and teaching space for the Department of Geology and the Engineering School. In May 2018 the Integrated Science Building (ISB) opened with 280,000 square feet of new laboratory and teaching space for the Department of Chemistry. Overall, the engineering expansion has resulted in the addition of over 30 new faculty members in the past five years.

Figure 1 provides a layout of the second floor in LEEP2 and the grey shaded area is M2SEC. The inset shows the entire engineering complex which also includes Learned Hall, Spahr Engineering library and Eaton Hall (red outlined areas are LEEP2 and M2SEC as shown in the overall diagram). LEEP2 has three floors (ground, first, and second) and is divided into teaching (east-end) and research space (west-end). For example, in Figure 1 rooms 2425 and 2420 as well as rooms to the east are new classrooms, graduate offices, and community spaces while the areas to the west are new research laboratories. The separation of classrooms and research labs provides a level of safety but at the same time convenient access for students (graduate and undergraduate) who are involved in research and simultaneously taking courses.

Figure 2 depicts a detailed layout of research labs 2444 and 2445. The hallway entrance to these labs as shown in Figure 1 requires key card access to enter from both the main corridor and stairwell at the opposite end. The lab locations and restricted access provide an initial level of safety from the classrooms as well as identification of students and staff who enter the hallway. The offices (2446 and 2447) were designed as separate spaces from the labs. The offices have no direct entrance into the laboratories which was done intentionally to prevent chemically contaminated materials from being brought into the offices [16]. Large windows were installed on both sides (East and West) of the offices for full visibility so that researchers can monitor the labs from either the office or hallway without having to enter the labs. Large windows were also installed in the exterior walls of the labs which provide natural light and the ability to see into the labs from outside the building. Emergency contact names and phone numbers for the Principal Investigator(s), graduate students and Environmental Safety and Health (EHS) are posted on each laboratory door. Additional safety features which are numbered (items 1-9) in Figure 2 are described in detail in the following sections.

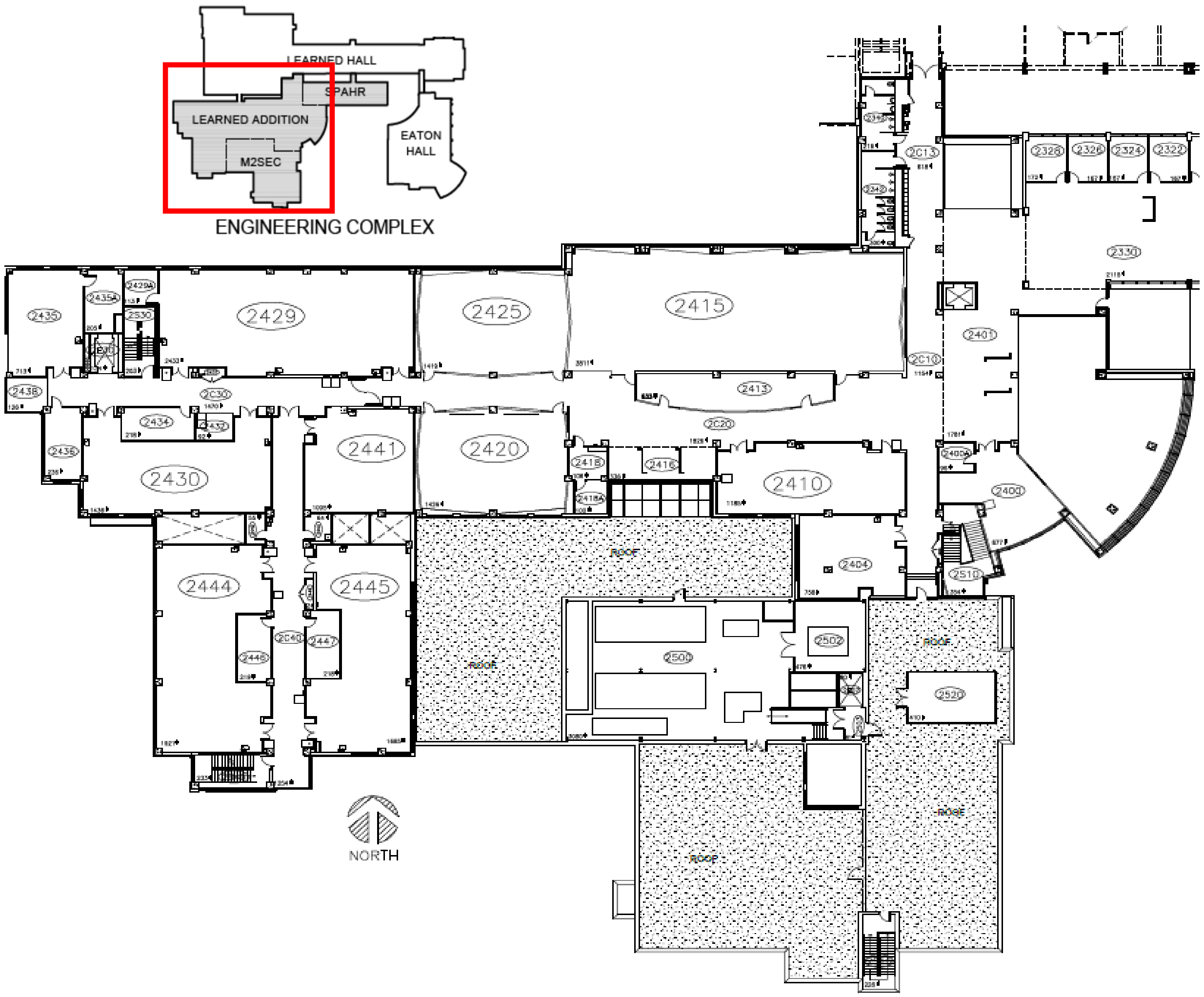

Figure 1 : Illustration of the Learned Engineering Expansion Project 2 (LEEP2), second floor. Inset shows the School of Engineering complex which includes Learned Hall, Spahr Engineering library, and Eaton Hall with the newest facilities outlined in red (Learned Addition or LEEP2 and M2SEC).

Laboratory Safety Equipment and Features

Personal Protective Equipment (PPE)

Personal Protective Equipment (PPE) is essential and often the first line of protection in the laboratory. Signs are posted on all laboratory doors and gas cylinder storage areas, “Notice Safety Glasses Required”. As shown in Figure 2, PPE is stored at the entrance to the laboratory (Figure 2, item 1) so that it is easily accessible when entering the lab. Safety glasses are available next to the four entrances and all other equipment is stored in PPE cabinets. Placing the PPE storage near the entrance makes it readily available to people entering the lab and provides a place to remove and store PPE when exiting. All PPE is required to stay in the lab to prevent chemically contaminated material from leaving the lab. Also, having a common PPE storage cabinet and coat rack provides a location for students and researchers to store specialized PPE such as gloves, chemical splash goggles, face shields and a location to hang lab coats.

Eyewash and emergency showers

Another requirement for general laboratory safety is eyewash (Figure 2, item 2a) and emergency shower stations (Figure 2, item 2b). Eyewash stations mounted on the sinks are located at both ends of the laboratories. Safety showers and additional eyewash stations are located just outside the entrance doors at either end of both labs. Providing emergency showers and eyewash stations outside the lab allows the occupant to exit the lab where the exposure or accident may have occurred. Activation of the safety shower in the hallway also alerts Environmental Safety and Health (EHS) that a shower has been activated and provides medical response with a location.

Figure 2 : Schematic of labs 2444 and 2445 and offices 2246 and 2247. Numbers designate the specific location of safety equipment located throughout the labs. General descriptions: Hoods, Ventilated Enclosures, Glove Boxes, and numbered items: 1. Personal Protective Equipment (PPE), 2. Eye wash and shower stations, 3. Fire extinguishers and fire alarms, 4. Ventilated dropdowns, 5. Interlock safety systems, 6. Gas detection systems, 7. Safety Data Sheet Compliance Center, 8. Ventilated cabinets, 9. Gas distribution panels. Numbers shown are referenced in the text.

Fire safety

Fire extinguishers (Figure 2, item 3a) are located near the north and south entrances to the labs and in a central location in the hallway. Fire extinguishers are type ABC and are meant for putting out trash-wood-paper (A), flammable liquids (B), and electrical (C) fires. Other fire extinguishers are purchased on a as needed basis depending on the specific hazard (e.g., Metal-X dry powder fire extinguishers for Class D fires involving combustible metals). Fire alarms and campus alert indicators are in the hallway and labs (Figure 2, item 3b). Activating the fire alarm in LEEP2 or M2SEC, alerts occupants in both buildings to evacuate and provides emergency response with a location.

Chemical fume hoods

Two types of chemical fume hoods (Labconco Corporation) are installed in the LEEP2 laboratories. Laboratory 2444 has two chemical fume hoods (6 ft and 8 ft lengths) with acid and base storage beneath the work area and two floor mounted fume hoods (8 ft and 12 ft lengths) for larger scale equipment as shown in Figures 2 and 3. Laboratory 2445 has seven chemical fume hoods (5 ft and 6 ft lengths) with acid and base storage and one floor mounted fume hood as shown in Figure 3. The air flow rates in all hoods are controlled to maintain a face velocity of 80 ft•min^{-1} when the sashes or doors are open. If the air velocity drops below 80 ft•min^{-1} an alarm sounds. All exhaust duct work from the fume hoods to the Strobic fans located on the roof are welded stainless steel to minimize corrosion and leaks. Additional ventilated dropdowns (Figure 2, item 4) are located thought the labs for equipment such as gas chromatographs, glove boxes, ovens and other emission generating equipment. The dropdowns are equipped with inline dampers to control ventilation flow or shut off ventilation if not being used.

Ventilated enclosures

Four custom designed ventilated enclosures were installed in labs 2444 and 2445 as shown in Figure 2. The enclosures are constructed using 80/20® extrusion (80/20® Inc., Columbia City, Indiana) and Lexan™ plastic sheeting (SABIC Plastics, Riyadh, Saudi Arabia) as shown in Figure 4. The transparent Lexan™ allows for excellent visibility while still providing good impact and chemical resistance. Sliding doors mounted on overhead rollers on both sides of the enclosure allow half the total length to be opened for moving large equipment in and out. The enclosures are equipped with removeable Lexan™ panels on both ends for feeding gas lines and electrical wiring. The panels can be easily modified to accommodate a variety of experimental requirements and replaced when projects are completed. A sprinkler head is mounted in the roof of the enclosure in case of fire. LED lights are mounted above the enclosures on both sides for increasing visibility when working on equipment inside. The interior enclosure volume is about 400 cubic feet.

The volumetric flow rate measured using a hot-tip anemometer is about 400-550 ft3 min^{-1} (dependent on enclosure location) with the doors closed. The enclosures were designed to maintain an air velocity of 30 ft•min^{-1} with an 18-inch door opening. Draeger Smoke Tubes (Lübeck, Germany) were used to conduct smoke tests when equipment was installed inside to ensure complete smoke containment when doors were opened to 18 inches.

Safety interlock system : The ventilated enclosures are equipped with safety interlock systems (Figure 2, item 5) designed to automatically shut off the gas supply or power to equipment located inside. The same general interlock system was designed and installed on each of the ventilated enclosures in lab 2444 as shown in Figure 4. Four conditions (high or low temperature, gas detection, crash button and exhaust flowrate) are monitored and wired in series as shown in Figure 6. All four conditions must be satisfied for the interlock system to operate. Specifically, the system is equipped with a Cal Control Model 3300 (Hertfordshire, UK) temperature controller, an emergency stop button, a Meridian Universal Gas Sensor from Scott Safety (Monroe, NC) and a Dwyer Model 3000-00 Photohelic to measure the differential pressure between the room and exhaust ventilation. The interlock system controls air-actuated valves and electrical relays. If an interlock is tripped (e.g., high temperature, gas detected, crash button depressed or differential pressure below minimum setpoint indicating low exhaust air flow), air is shutoff to normally closed valves for controlling gases that feed equipment inside the enclosure and electrical relays are opened to turn off power to equipment inside the enclosure. When the condition is resolved (i.e., temperature decreases below alarm setpoint, emergency stop button is pulled out, gas no longer detected or ventilation flow rate back to normal) the interlock system must be reset manually by the student or researcher before equipment will turn back on.

In addition to the interlock systems built into the ventilated enclosures, other equipment throughout the labs are equipped with interlock safety systems. For example, most ovens and furnaces come equipped with only one temperature controller. A second temperature controller is installed into the ovens and furnace with a separate temperature measurement (e.g., thermocouple) for redundancy. Two controllers with independent temperature sensors helps ensure if the primary controller fails that the secondary controller will shut off the equipment in case of a temperature runaway. We have also built portable interlock systems that can be used for a variety of experiments to monitor temperature, pressure or flow rate where unattended operation maybe required, and an interlock system is necessary.

Gas Detection System : The Meridian Universal Gas Sensor connected to the interlock systems is one part of a larger, networked Scott Gas Safety system. The system in composed of a QuadScanII, Model 7400 receiver (Figure 2, item 6a) that interfaces with Freedom 5000 toxic gas sensors (Figure 2, item 6b) and Meridian Universal gas sensors (Figure 2, item 6c). All the QuadScanII controllers are mounted on the exterior of the ventilated enclosures as shown in Figure 4 and a description about the sensors is provided in Table 1.

For example, the north side of lab 2444 has a ventilated enclosure and two floor mounted hoods that are all equipped with gas detectors. The hoods and ventilated enclosures are equipped with Meridian Gas Detector that use combustible, catalytic bead gas sensors.

As shown in Figure 4, on the outside of the ventilated enclosure is a Freedom 5000 Sensor (blue) next to a QuadScanII Controller. The QuadScanII provides a user interface for setting alarm levels and viewing warnings. Acceptable gas levels can be specified depending on the type of gas and set to trigger a “Warning” and/or “Alarm” states.

Figure 3: Labconco Chemical Fume Hood (left) with acid and flammable liquid storage cabinets located beneath the hood countertop, Labconco Floor Mounted Fume Hood (right).

Figure 4 : Photo depicting the custom ventilated enclosure located at the south end of lab 2444. The dimensions (h x l x w) are 8 ft 10 inches x 10 ft x 5 ft 4 inches. The photo shows the attached gas detection system (front left), warning/alarm lights (top runner), interlock system (front right), colored outlets, safety equipment inspection tags, and PSM documentation (white folder next to computer tower).

Table 1: Location of the QuadScan II monitoring systems in Lab 2444 and the corresponding sensor types.

QuadScan II Ventilated Enclosures	Meridian Sensors	Sensor Type	Freedom 5000 Sensors	Sensor Type
North	3	Combustible	1	Hydrogen
Middle	1	Ammonia	1	Ammonia
South	1	Combustible	1	Oxygen

For example, the combustible gas detectors are set for a "Warning" if 25% of the Lower Explosive Limit (LEL) is detected and set for an "Alarm" if 50% of the LEL is detected. When a warning is triggered, an amber strobe light is activated above the individual QuadScanII location, see Figure 4. When an alarm is triggered, a red strobe light and siren are activated, (Figure 4). Visually, the lights can be observed from the offices or hallway and the QuadScanII can indicate which enclosure has encountered the leak. In addition to the audible and visual alarms, the enclosures are equipped with a Yokogawa Modular GM10 Data Logger (Sugarland, TX) which is programed to send an alert message if a gas detector triggers a warning or an alarm or the Photohelic® detects that the ventilation has dropped below the minimal setpoint. The messages are sent to the lab researchers and students via text and email and will indicate the type of alarm (i.e., type of gas, concentration level (ppm or % LEL), or low ventilation flow rate).

Electrical safety

All the electrical outlets in the lab are labeled which identify the electrical panel and breaker number. Warning placards on the electrical panels indicate the hazards and minimum PPE required for opening the panel door. The lab is equipped with both 120 and 220-volt power and the outlets have distinct plug and receptacle prong orientation that is dependent on the voltage and amperage output. Three sources of power are available with color coded outlets (grey for house power, red for generator power and blue for uninterruptable power).

In the event of an electrical outage, the back-up generator provides backup power within 10 to 15 seconds and the system is tested monthly. LEEP2 has three Strobic fans for fume hood ventilation and one remains running in the event of a power failure on generator power to provide limited hood exhaust. Lab 2444 is setup with four uninterruptable power supplies (Toshiba 1600EP Series, 6kVA) which provide both 120 and 220-volt power to equipment operating in the ventilated enclosures, computers running the equipment, QuadScanII gas monitoring systems, and ventilated enclosure interlock safety equipment.

Chemical Safety

In general, chemicals are segregated according to compatibility. Acids and flammable liquids are stored in dedicated cabinet locations beneath the ventilated fume hood as shown in Figure 3. In addition, storage areas beneath hoods are ventilated and have secondary containment in case of a spill. Volatile compounds are stored in the ventilated cabinet and water sensitive substances are stored in two chemical dry boxes located at the south end the lab. A chemical database (ChemInventory) is used which contains the safety data sheet (SDS) and location of each chemical in the lab. Safety data sheets can also be found in the lab with the experiments and in the SDS Compliance Center by the lab entrance (Figure 2, item 7).

Chemical waste containers are located near the north and south lab entrances. Each location has a halogenated and non-halogenated waste container that is disposed of by EHS when full. Waste containers for specific waste streams can be ordered by EHS upon request and all containers are appropriately labeled. Waste container labels designate the type of waste, provide contact information, and list the contents of the container [18]. After contacting EHS, the 'pickup request date' is updated and the waste is removed the following day.

Gas storage and handling

Flammable Gas : A unique feature not found in many academic laboratories is the flammable high-pressure gas cylinders are stored outside of the building (Figure 2, item 8a) and the gases are piped into the labs. This practice is more common in industry but should be considered in the design of any new academic laboratory. Figure 5 shows the addition which was built on the outside of the LEEP2 building. The building has a secure entrance with concrete floor an open roof for ventilation. Inside the addition there are three gas cylinder cabinets.

Each cabinet can hold up to three high-pressure flammable gas cylinders. The gas cabinet provides protection of the flow components (i.e., regulator and pressure relief device) from the weather. The standard connection to all flammable gas cylinders is a two-stage regulator, excess flow valve, flame arrestor, and pressure relief device. Stainless steel tubing (0.25-inch diameter) and compression fittings (Swagelok®) were used to pipe the cylinder gases into the building, through a plenum in the wall, and up two floors to the labs (2444 and 2445).

A continuous run of tubing was used inside the plenum without any unions. The wall plenum is monitored for gas leaks using a Kele, E3SA combustible gas sensing system (Figure 2, item 6d). Two additional ventilated gas cabinets are located at the north and south ends of labs 2444 and 2445 as well as a smaller single cylinder ventilated cabinet is located at ventilated enclosure #2, (Figure 2, item 8b). The ventilated cabinets located in the lab are for storing flammable, toxic or specialty gases that are connected to specific experiments.

Non-flammable Gas Storage : Non-flammable gas cylinder storage for labs 2444 and 2445 is in a hallway closet as shown in Figure 2. The closet has room for storing nine high-pressure nonflammable gas cylinders. The cylinder closet contains an Oxigraf oxygen monitoring system (O_2iM) which monitors the O_2 level in the closet. If the level drops below 19.5 vol.% O_2, the system has both an audible alarm and an indicator light that will illuminate in the hallway (Figure 2, item 6e). The status indicator will also show if the system has a fault or needs calibration. The nonflammable gases stored in the closet are distributed throughout both laboratory spaces to gas manifolds located at the end of the ventilated enclosures (Figure 2, item 9) or inside the hoods. Other non-flammable gas cylinders can be secured near equipment in the labs when necessary.

Figure 5: Left: Outdoor flammable gas storage building (7.5 ft × 12 ft) with open roof and concrete floor (note concrete sidewalk for wheeling cylinder carts). Gases are piped into the lab to distribution panels located at the ends of the ventilated enclosures and inside hoods. Right: Ventilated gas cabinet (Safety Equipment Corporation, 7000 series) designed for storing flammable and toxic gases located in the lab.

Additional gas cylinder storage with bins and chains for restraining cylinders is located outside of LEEP2 and M2SEC in locked fenced areas. Gas cabinets containing shelves with chains in these areas are used to secure smaller gas cylinders. Gas valve handles in the lab at the gas distribution panels (Figure 2, item 9) are color coded to designate the type of gas and the source location as shown in Table 2.

The minimum PPE requirements for transporting cylinders consist of safety glasses, leather gloves, and steel-toed shoes. Gas cylinders are transported with the caps on using a cylinder cart with cylinder restraint (chain or strap). All gas cylinders are secured to the wall or gas cabinet using chains and regulators are tethered to the wall using a metal cable attached to Unistrut. All gas lines are equipped with pressure relief devices and were pressure tested for leaks using helium and Snoop™ liquid leak detector.

Safety Management and Training

Process safety management

A process safety management (PSM) program was prepared to identify hazards in the laboratory and determine the level of analysis required before running any equipment or experiments. A simple to use Hazards Analysis Checklist (HAC) was developed to determine the level of hazard review required as shown in Table 3.

The checklist was developed based on a similar guideline that was used in DuPont Central Research and Development. For example, if a student is working with a chemical with a Hazardous Materials Identification System (HMIS) health rating of 0 this is considered a "Minimal" hazard. If the HMIS chemical health rating is 1 or 2 the hazard is defined as "Low". If the HMIS chemical health rating is 3 the hazard is defined as "Moderate" and if the HMIS chemical health rating is 4 the hazard is defined as "High". Another example might involve temperature. If the temperature is between -30 to 60°C then the hazard is designated as "Minimal", but if the temperature is outside of this range (e.g., < -30°C or > 60°C) then temperature is considered a "Moderate" hazard.

Table 2: Gas type, valve handle color, and gas location.

Gas Type	Valve Color	Source Location
Helium	Blue	Hallway storage
Argon	Orange	Hallway storage
Nitrogen	Black	Hallway storage
Carbon Dioxide	Grey	Hallway storage
Oxygen	Green	Hallway storage
Air	Yellow	Hallway storage
Flammable	Red	Outside and in ventilated cabinets*
*Ventilated cabinet locations are shown in Figure 2 (item 8b).		

Table 3: Hazards Analysis Checklist (HAC). The first document to be completed which identifies the level of hazard review required and helps to identify other PSM documents to be completed. If any item is checked in a column that determines the minimum level review required. The level of review required for "Minimal" hazards is student to student; "Low" hazards is student and advisor, "Moderate" hazards is student, advisor and technical expert, "High" hazards is student, advisor, technical expert and Environmental Health and Safety.

Level or Review & Checklists Required[a]	**Minimal**	**Low**	**Moderate**	**High**
Materials and Products				
HMIS- Flammability (Volume <1L)	☐ 0-1	☐ 2-4		
HMIS- Flammability (Volume ≥ 1L)	☐ 0	☐ 1-2	☐ 3-4	
HMIS- Flammability (Volume ≥ 1L) under pressure or above flashpoint	☐ 0		☐ 1	☐ 2-4
HMIS- Reactivity	☐ 1	☐ 2	☐ 3-4	
HMIS- Health	☐ 0	☐ 1-2	☐ 3	☐ 4
Capable of Generating of Strong Odors	☐ No		☐ Yes	
Biological Materials		☐ Yes		
HIGH OR LOW TEMPERATURES – SURFACE	☐ > -30°C (-20°F) or <60°C (140°F)		☐ < -30°C (-20°F) or >60°C (140°F)	
HIGH OR LOW TEMPERATURES – INTERNAL TEMPERATURE OR EXOTHERMIC REACTION	☐ <60°C (140°F)		☐ >60°C (140°F) or reaction boiling	
EQUIPMENT UNDER PRESSURE/VACUUM	☐ Atmospheric Pressure	☐ Vacuum and 0-40 PSIG pressure for shielded glassware; rated vessels	☐ Unshielded glassware; non-rated vessels; >40 PSIG	
GASES- flammable, toxic, corrosive			☐ Yes	
GASES		☐ In Cylinder closet/hood	☐ Outside cylinder closet	
ELECTRICAL- Voltage	☐ < 110V	☐ 110-120V	☐ 208-220 V Protected	☐ >220V Protected
MECHANICAL MOTION			☐ Yes	
VENTILATION REQUIRED-fume hood		☐ Yes		
COMPUTER AND AUTOMATED CONTROL SYSTEMS			☐ Yes	
WORKING ALONE			☐ Yes	
UNATTENDED EXPERIMENTS- with proper interlock/safety system			☐ Yes, minimal hazard	☐ Yes > minimal hazard
LABORATORY ERGONOMICS		☐ Repetitive motion >4 hours/day or awkward height/posture		
NOISE LEVEL/NOISE CONTROL	☐ <85 dBA		☐ ≥85 dBA	
IONIZING RADIATION – SEALED RADIOACTIVE SOURCES			☐ Yes	
IONIZING RADIATION – UNSEALED RADIOACTIVE MATERIALS			☐ Yes	
IONIZING RADIATION – X-RAY		☐ <20 kv	☐ ≥20 kv	
NON-IONIZING RADIATION – INFRARED, MICROWAVE, RADIO, ULTRAVIOLET		☐ <TLV	☐ ≥TLV	
NON-IONIZING RADIATION – LASERS		☐ Class I - IIIA	☐ Class IIIB - IV	
NOVELTY- New Technology		☐ First time running experiment		☐ Unknown reactions
LEVEL OF REVIEW: Complete EHS Hazard Review Document if Moderate or High Risk	☐ Minimal	☐ Low	☐ Moderate	☐ High

Once all the hazards are identified, the level of review is determined by the box(s) checked with the highest level of hazard. If all the hazards identified are "Low" then the hazard review can be conducted between two students (student to student). If any of the hazards identified are in the "Minimal" category, the hazard review must be conducted between the student and advisor. If any of the hazards identified are in the "Moderate" category, the hazard review must be conducted between the student, advisor, and a technical expert when necessary. If any of the hazards identified are in the "High" category, the hazard review must be conducted between the student, advisor, technical expert, and a representative from EHS. An example when a technical expert maybe required could include working with equipment operating at 208-220 volts which is defined as a "Moderate hazard". If the advisor is not familiar with the hazards associated with high voltage, they should consult an expert to provide additional guidance during the process safety review. If the advisor is familiar with the hazard, then they can serve as the technical expert. Examples of high hazard categories include: HMIS flammability rating 2-4 under pressure or above flash point, using chemicals with HMIS health rating 4, using electricity greater than 220 volts, unattended experiments with greater than minimal hazard in any other category, and conducting experiments with unknown reactions. Again, the high hazard category requires the student, advisor, technical consultant and EHS to be involved in process safety hazard reviews before equipment or experiments can be started. In addition to determining the level of review, the document also helps to identify the other PSM checklists, described in Table 4 that need to be completed.

The complete PSM binder contains the HAC, the completed PSM checklists for each identified hazard, EHS training certificates, standard operating procedure (SOP), emergency shutdown procedure, safety data sheets, mechanical and/or process diagrams, equipment user manuals, mass and energy balances and authorized users signature page. Completed PSM documents are stored electronically in a share drive that is accessible to all students and researchers. Paper copies are kept for quick reference next to the equipment or experiment in white 3-ring binders. The PSM binder serves as a great training tool for incoming students and provides examples for how to prepare a process safety plan.

Labels, tags, signage

All chemical samples are labeled with chemical name, notebook number, researcher initials and date. Inspection tags on equipment such as the interlock system shown in Figure 6 remind researchers when the system was last tested. Inspection tags can be found on the fire extinguishers, eyewash stations, emergency showers, and gas monitoring systems. Tags are also attached to pressure relief devices to indicate the gas, set pressure, and installation date. The lab has also developed a formalized placard to be placed on hoods and ventilated enclosures or near experiments when "Experiments in Progress". The placard has emergency contact information, start/end date and time, a notebook and page number, the general hazards and brief description of the experiment.

Safety inspections

Bi-monthly : The researchers test the eyewash stations and safety showers every two weeks to ensure they are functioning properly. This also flushes the lines with fresh water to reduce contamination and rust. The fire extinguishers are also checked to ensure that the pressure is within an acceptable range.

Monthly : A standard checklist is used for monthly safety inspections to ensure proper sample labeling, housekeeping, PPE is available and functional, proper chemical, flammable and gas cylinder storage and waste handling, to name a few. When conducting the inspections, the researchers provide comments as to the improvements that should be made, inspection sheets are distributed and archived, actions are taken to address any issues and the items are discussed during lab group meetings. It is particularly important to note here that following-up on issues identified during safety inspections and taking corrective action in a timely manner is imperative for the process to be effective.

Quarterly : Quarterly inspections are conducted on equipment with interlocks which includes the gas detection systems and controllers that monitor for high-temperature, high-pressure or low ventilation conditions. Interlock devices are checked by testing the system. For example, calibrated gas standards are used to check that the gas monitors measure the proper concentration and the alarms activate (lights sirens, valves close, equipment turns off). Once the inspection is complete the Quarterly Inspection tag is signed and dated as shown in Figure 6 for the interlock system. EHS also inspects the eyewash stations and safety showers located in the labs and hallways every three months.

Annually : Every April the lab takes one entire day to focus on safety. The "Safety Day" is set aside for the PI and students to focus on updating safety items. Examples include, lab clean up, check/update chemical and equipment inventories, review and update PSM documentation, check that SDS forms are up to date and available, and disposal of unwanted samples and chemicals.

Safety Training

Laboratory On-boarding and EHS safety courses :

As a part of the on-boarding process, students are provided with a 'Safety Training Checklist' that provides a list of EHS safety courses that must be completed and documented. The researcher supervisor discusses with each student the topics that they should review. Over seventy topics are available through Blackboard Learn^{TM} which include specific courses such as chemical segregation and storage, chemical fume hood (operation), waste management 101, and fire safety to name a few [17]. The checklist also requires that a tour of the lab be provided to familiarize students with the specific safety features. A specific requirement for undergraduate researchers is that they are not allowed to work in the lab without a graduate or post-doctoral researcher present.

Laboratory Off-boarding : A common problem in many academic labs is students graduating or leaving the laboratory without disposing of their chemical samples. Before a student departs, they must complete an off-boarding process which includes disposal of all chemical samples, decontamination of equipment, returning laboratory notebooks and keys and an inspection by the research supervisor of their laboratory area.

Monthly safety meetings : Our lab works closely with The University of Kansas Center for Environmentally Beneficial Catalysis (CEBC). The CEBC holds monthly safety meetings similar in format to industry safety meetings. All graduate students and post-doctoral researchers working on CEBC projects are required to attend the CEBC monthly safety meetings. The meetings begin with a presentation by the CEBC safety committee to review issues found during monthly safety inspections. The safety committee is made up of faculty, staff, and students. A presentation led by a member of the safety committee on a variety of topics (chemical safety, electrical safety, safe driving, off-the-job safety, etc.) is presented each month. External speakers also provide training on specific subjects such as waste management and Right-to-Know topics. Fire extinguisher training is offered yearly by EHS so that students and researchers get "hands-on" experience with extinguishing a controlled fire. The goal of these meetings is to provide safety information, reinforce a safety culture and promote participation in safe workplace activities.

Safety Incident and Reporting : In the case of a laboratory incident, emergency contact information is located at the laboratory entrances. Depending on the severity of the situation, contact information is provided for a primary and alternate contact, the laboratory principal investigator, department, public safety office, EHS, EHS 24-hour emergency contact, and 911. All accidents are reported to EHS and if an accident involves injuries then Human Resources are contacted to investigate. Near misses are reported to the laboratory PI, discussed among the laboratory group, and preventative measures are taken to avoid similar situations in the future. A land-line phone is available in the student offices. It is particularly important to have an available means of contacting emergency services in case of a cell phone outage or lack of cell phone service.

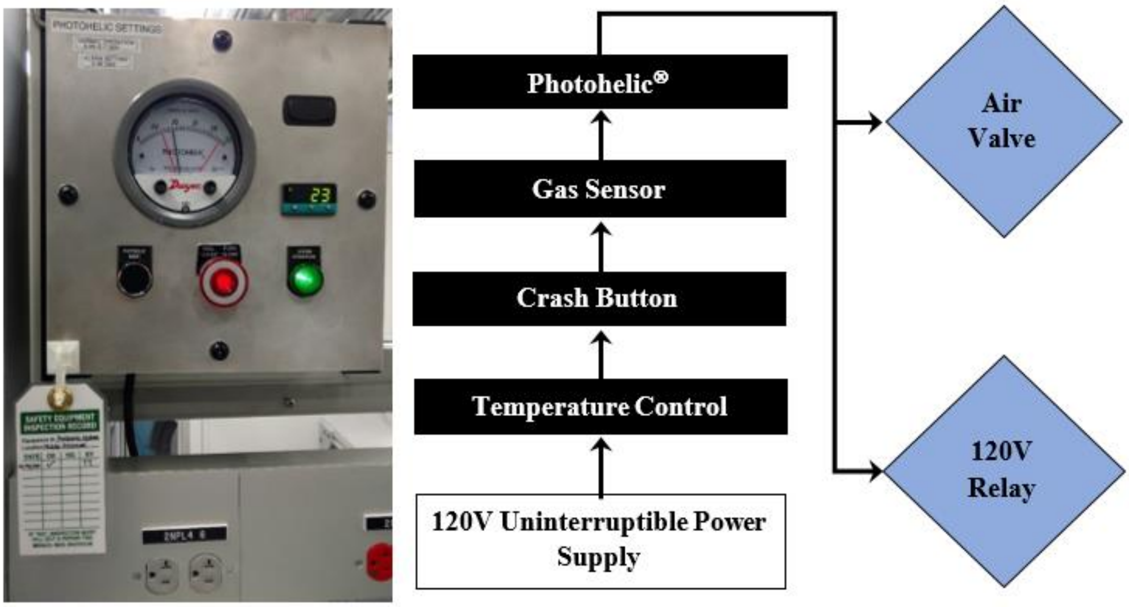

Figure 6 : Custom interlock system (left) with quarterly interlock inspection tag (green tag). Green light on right indicates no faults. If light goes out, interlock is tripped, and condition must be corrected so that black button on left can be depressed to reset system. Flow diagram for interlock sequence (right) used for equipment operated inside ventilated enclosures. If temperature exceeds setpoint, crash button is depressed, gas sensor alarms or Photohelic® detects low differential pressure (i.e. low ventilation exhaust flow rate) then air turns off to air-actuated valves which shuts off gas supply and electrical relays open which shuts off power to equipment inside enclosure.

Table 4 : Description of the PSM checklists.

Document	Description
Electrical	Identifies the electrical requirements and compatibility. Checks for proper grounding, wiring, and use of interlocks. Identifies potential for stored energy, uninterruptible power sources, the panel and breaker location, and the consequences of power loss and restoration.
Emergency and Operating Procedures	Requires written standard operating procedures for start-up, operation, shut down and decontamination. Also requires emergency shutdown procedures to be written and additional hazards to be identified. Identifies emergency crash buttons, shutdown systems, and PPE required.
Environmental	Requires waste disposal method to be identified and an example waste label to be attached. Identifies special waste concerns, the amount of waste generated, emissions, and planned discharge into drains. Provides useful information and links about Environmental Health and Safety.
Equipment Under Pressure	Identifies the source, operating, maximum allowable working pressure, and proper pressure relief setpoint. Ensures material of construction for all equipment is compatible with process materials. Identifies the hazards of headspace expansion, decomposition, leaks, and general equipment failure. Ensures relief device is the proper pressure, rated for proper temperature, compatible with fluid (gas/liquid), and are pointed in a safe direction.
Laboratory Area	Identifies hazards to others in the laboratory area and describes special requirements and PPE for personnel entering the area. Identifies the need for alarms and barriers. Requires a location description of the nearest fire alarm, extinguisher, two emergency exits, safety shower, eyewash station, emergency contact information. Identifies "lone workers', afterhours operation, and unattended experiments. Requires that the SOP, emergency shutdown procedure, emergency spill procedure, and EHS safety documentation be readily available.
Gases	Requires the identification of the gas supply (house, cylinder, etc.), equipment pressure limitations, material/gas compatibility, relief device set point, and the need for interlock systems and gas sensors. Questions researcher about gauge visibility, regulator conditions, and precautions taken in the case of a pressure system failure or when using a toxic gas. If gas is flammable, researcher is prompted to complete flammable "Flammable Gases, Liquids, Solids" checklist.
Flammable Gases, Liquids, Solids	Identifies the type of material and establishes the possibility and potential causes for reactivity, explosion, and decomposition. Also points to ignition and additional fuel sources. Requires a list of the precautions taken and automatic detection devices present.
High or Low Temperature	Identifies the operating temperature range, surface temperatures, PPE required, method of heating or cooling, the consequence of rapid temperature change, and need for interlock devices. For interlock devices, the checklist identifies whether a secondary controller and thermocouple is installed as a backup to the primary controller.
Raw Materials and Products	Researcher is required to provide a process description (to include reaction chemistry) and MSDS for all reactants, products, and intermediates. Also requires researcher to provide a process flow diagram, heat balance and material balance if applicable. Questions about the transport, safe handling, and emissions of chemicals. Requires a list of raw materials and intermediates in a table that evaluates the quantity and potential hazards involved with using the chemicals.
Mechanical Motion	Identifies hazards involved with motion to include: rotating, pinch points, sliding, reciprocating, cutting/sharp edges, oscillating, stored potential energy, belts/chains, and others. Requires description of safety precautions, guards, and lock-out devices used to prevent injury.
***Authorized Users**	This document lists the name and signature of individual trained on the equipment or experiment. The document is also signed by the advisor stating that the hazard assessment has been performed and that the listed people are authorized to run the equipment or experiment.
****Management of Change**	Document is filled out when an experiment changes personnel, procedure, or configuration. This form documents the change, describes any issues, and identifies the type of Hazards reviewed due to the change. It is required that a detailed description of the corrections be made and that the changes be approved by a supervisor before operation.

* Authorized users document is completed after individual's training is complete
** Management of change is filled out upon change in process, then all other PSM documents are reviewed again

Conclusions

New state-of-the-art research and teaching facilities have been built at the University of Kansas for the School of Engineering and the College of Liberal Arts and Sciences which have created the opportunity to design and implement safe and more efficient laboratory space and practices. A total of nearly 600,000 square feet of research and teaching space has been completed and opened in the past six years. Examples of the safety features and equipment incorporated into the design of a new chemical engineering laboratory include: building layout, engineering systems (fume hoods, ventilated enclosures, exhaust fans and back-up generators for electricity), lab safety equipment (gas monitors and interlock systems), chemical storage (flammable gases stored outside and piped into building), and process safety management (hazards analysis checklist, PSM, safety inspections). Successful implementation of laboratory safety should consist of inherent, passive, active and procedural approaches. A safety "culture" can be established in academic laboratories with strong leadership, teaching, communication and collaboration and active participation by all members of the lab group, department, or center. The examples presented in this contribution identify best practices and standards of design implemented in our laboratory that help foster such a safety culture. In addition, the presented approaches can serve as a practical example to new or existing laboratories that wish to implement similar safety practices.

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